Assimilation Versus Accumulation of Macro- and Micronutrients in Soils: Relations to Livestock and Poultry Feeding Operations[1,2,3]

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Primary Audience: Extension Personnel, Consultants, Nutritionists

SUMMARY

Nutrient management is an integral part of profitable agrisystems, but in some areas of the United States, continued applications of fertilizer and manure nutrients in excess of crop requirements have led to a buildup of nutrient concentrations that are of environmental concern. Proper use of nutrients in livestock manures is becoming more critical for sustainability of concentrated animal feeding operations (CAFO) because new environmental regulations require that nutrients be properly applied and managed. Losses of nutrients, such as N and P can be reduced by refining the rations fed, increasing nutrient retention by livestock, moving manures from areas of surplus to deficiency, finding alternative uses for manure, using cropping and haying systems that remove excess nutrients, and using conservation practices, such as limited tillage, buffer strips, and cover crops to limit runoff and leaching. Whole farm nutrient balances are useful for educating producers about quantities of nutrients being managed and the flow of nutrients, but they can also be misleading because of spatial factors, such as uneven nutrient application that introduce environmental risks that may not be noted with a whole-farm nutrient balance. Manure utilization plans also need to deal with nutrients that potentially leave the field or production area in route to sensitive ecosystems.

Key words: nutrient, manure, poultry, livestock, assimilation, accumulation, soil

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DESCRIPTION OF PROBLEM

American livestock production has changed dramatically over the past 3 decades. As livestock and poultry production have become more spatially concentrated, the quantity of manure nutrients relative to the capacity of local farmland to assimilate those nutrients has grown, especially in high production areas [1]. The number of counties in which the production of recoverable manure nutrients exceeds the assimilative capacity of the cropland and pastureland in the

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[2]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion of other similar products by USDA-ARS.

[3]Throughout the manuscript the terms animal or livestock are intended to include poultry.

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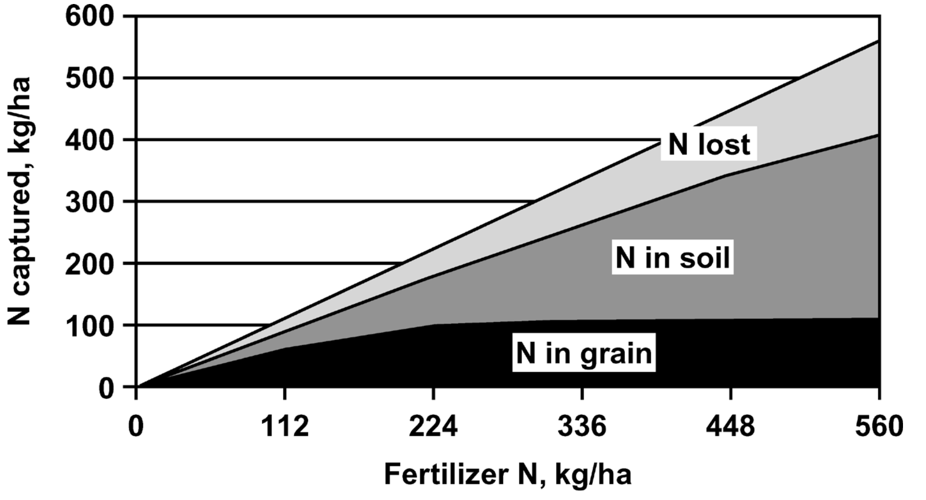

FIGURE 1. Relationship between fertilizer N inputs to corn and N captured in corn grain, N in soil, and N lost (Legg and Meisinger [5]).

county has increased dramatically since 1982 [2]. Today at least 2 to 5% of counties produce more manure than can be assimilated by total cropland and pasture in the county—mostly in North Carolina, the Chesapeake Bay area, Southeastern states, and California [1, 3, 4].

Numerous studies have demonstrated that swine manure effluent, dairy manure, poultry litter, beef feedlot manure, and the compost of these manures can be valuable fertilizers on crops, but overapplication can have detrimental effects on yield and soil properties. Excessive application of manure and fertilizer can lead to accumulation of nutrients in soils and to increased losses of N via volatilization, leaching, or runoff [5] (Figures 1 and 2). Today, an increased desire is that agricultural operations be sustainable. Thus, it is essential to maintain soil fertility and quality while minimizing any potential negative impacts on surrounding ecosystems. The objective of this manuscript is to briefly review current research that can be used to improve livestock manure use while minimizing potential adverse effects on the environment.

New Nutrient Management Regulations

Until recently the major regulations regarding manure from animal feeding operations (AFO) concerned the capture and control of runoff from pen areas, and there were few regulations concerning the use of manure collected from concentrated animal feeding operations (CAFO). However, with the advent of the new Environmental Protection Agency's Clean Water Regulations [6, 7], proper use of manures to avoid contamination of surface and groundwaters is required. All CAFO and many smaller AFO must have comprehensive nutrient management plans, and manure nutrients must be applied to farmlands at no greater than agronomic rates—i.e., rates that do not oversupply nutrients to crops or other vegetation. Thus, meeting nutrient application standards may require an AFO to spread manure over a much larger land area than they currently use. Ribaudo [8] reported that only 18% of large hog farms and 23% of large dairies currently apply manure on enough cropland to meet an N management plan. Lander et al. [2] estimated that only 20 (P basis) to 50% (N basis) of AFO operate with enough land to meet new land application requirements.

To meet new standards, the annual net income of livestock and poultry farms could be decreased by more than $1 billion (approximately 3%) annually. However, the actual outcome depends on the willingness of cropland and pastureland operators to substitute or replace commercial fertilizers with manure.

Manure as a Fertilizer

Mismanagement of manure when applied to crops or forages can result in runoff of nutrients

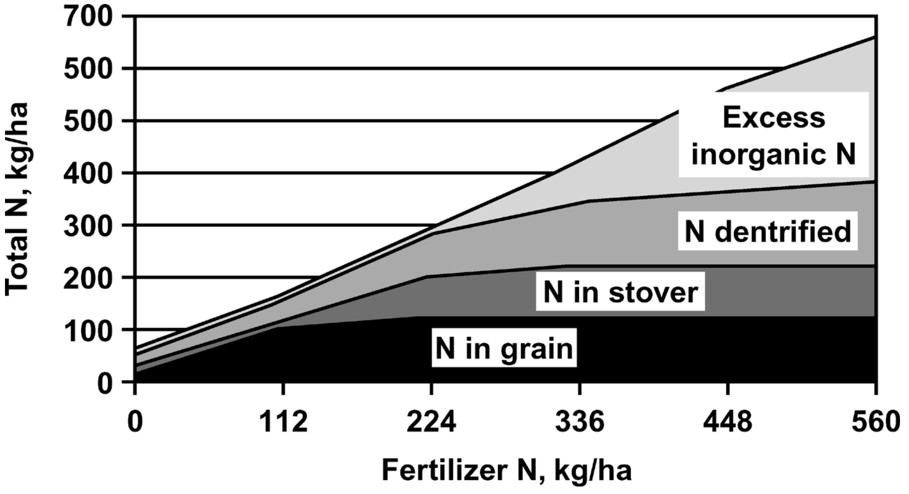

FIGURE 2. Average annual distribution of total N inputs in irrigated corn grown on sandy loam soil (Legg and Meisinger [5]).

or pathogens to surface waters, percolation of nutrients to groundwaters, accumulation of nutrients in the soil, or loss of significant quantities of N and C to the atmosphere. Many farmers prefer to use commercial inorganic fertilizers rather than manure or litter because of factors, such as uncertain and inconsistent nutrient content, difficulties in uniform spreading, soil compaction, odor, weed seeds, high salt content, personal opinions, and transportation costs. Increased paperwork from regulations could potentially further decrease use of manures by farmers.

The composition of manures collected from CAFO vary greatly depending upon animal species, the diet fed, length and type of storage, type of housing, timing and method of manure collection, pen surface, location in pen, bedding or litter used, application systems, and so on. [9, 10] (Table 1). Most field crops and forages require a N:P ratio ranging from 5:1 to 8:1. Because N may volatilize rapidly from manure as ammonia, N_2O or N_2 gas, in general, the N:P ratio of manures is less than the N:P of the diet and less than required by most field crops or forages.

Nutrient Conversions in the Soil

Capacity of Soils to Accumulate Nutrients. Most soils have the capacity to bind nutrients in significant concentrations; nonetheless, some nutrients can accumulate in soils to the point of becoming toxic to plants [11] or may be sources of nutrients to neighboring ecosystems. Soils remove ions from the solution phase by adsorption, fixation, and surface precipitation reactions. These mechanisms, collectively referred to as sorption, play a major role in regulating solution concentrations of nutrients and, consequently, their mobility and availability to plants.

TABLE 1. Range in nutrient analysis of manures for various handling systems (Klausner et al. [9])

System and nutrient	Dairy	Beef	Swine	Poultry
Nonliquid systems (kg/Mg)[1]				
N	2.5 – 8	2 – 10	1.5 – 13.5	2 – 55.5
P_2O_5	1 – 8	0.5 – 6.5	0.5 – 31	0.5 – 48
K_2O	1 – 15.5	1.5 – 14.5	1 – 9	1 – 27.5
Liquid system (kg/1,000 L)				
N	0.4 – 6.1	0.7 – 4.4	0.1 – 7.3	4.2 – 9.0
P_2O_5	0.2 – 2.5	0.1 – 3.5	0.1 – 7.6	1.6 – 10.9
K_2O	0.2 – 7.0	0.6 – 3.6	0.1 – 5.9	1.6 – 4.7

[1]Mg = megagram.

The bioavailability and mobility of nutrients in soils depends to a large extent on the soil's mineralogy and reactive surface area, the chemical and physical soil environment, and the amount and type of fertilizer applied.

Sorption mechanisms in soils include 1) ion exchange-weak electrostatic interactions between charged colloids and counterions in solution, 2) fixation-specific adsorption, whereby an ion is chemically coordinated to a surface functional group, and 3) diffusion of inorganic species into the solid phase. Cation exchange is a chief mechanism for the adsorption of alkali and alkaline earth metals, NH_4^+, and some heavy metals. Most soils also contain a small amount of anion exchange capacity derived from Fe and Al oxides and edges of layer silicate clays. In highly weathered or volcanic soils, anion retention can significantly retard leaching losses of mobile solutes, such as nitrate [12].

Specific adsorption of nutrients through ligand exchange on hydroxylated surface sites of oxides or edges of layer silicate clays is an important mechanism for the relatively high energy binding or fixation of oxyanions (e.g., phosphate, sulfate, selenite, arsenate, and organic acids). Heavy metals (e.g., Cd, Cu, Pb, Ni, Zn) can also be strongly sorbed onto the surface of silicate clays. Decomposition products of manures (e.g., humic acids) may substantially increase sorption of these heavy metals by increasing the number of binding sites on humic-coated mineral surfaces at a low pH. Alternatively, at high pH, humic acids may form aqueous complexes with metals that have greater mobilities than noncomplexed forms [13].

Precipitation and dissolution of minerals in soils are important thermodynamically driven processes that can influence the concentration of inorganic species in solution. In soil systems, precipitation of dissolved ions is greatly facilitated by the presence of mineral surfaces. In addition, precipitation and dissolution reactions are controlled by poorly crystalline (amorphous) mineral phases. These factors complicate the estimation of the soil solution concentrations of nutrients that are subject to transport.

Because many nutrients and trace elements in animal manures are organically bound or contained within structural components, their mobility and availability is not straightforward. For instance, nitrogenous compounds in manures require biologically mediated mineralization to inorganic forms (e.g., the conversion of urea and amino acids to ammonium) before they can be used by plants. Most soils have limited capacity to store N because soil N accumulates in association with C as soil organic matter, which is maintained at a quasi-steady-state condition, depending on tillage practices, cropping systems, climate, and so on. Nitrogen can be temporarily stored as nitrate, but this readily soluble form can be rapidly leached below the root zone. Because N sources are only temporarily stored in soil, N additions are normally applied just before the active uptake stages of the crop. Much of the N in manures is in organic forms that are released more slowly than commercial inorganic fertilizers.

Reliable predictions concerning the mobility and bioavailability of nutrients and trace elements in soils is difficult because of the vast array of sorption processes, microbial processes, time scales of reactions, soil mineralogies, and the effects of competing anions, cations, and humic acids in the soil solution. Moreover, determining an environmentally acceptable retention capacity has been difficult because erosion potential and management effects add complexity in determining tolerable losses of soil P and other nutrients [11]. Nevertheless, regulatory agencies in many states are establishing upper limits for soil test P; some are at levels only marginally above the crop response level but many at levels 2 to 3 times higher than crop response levels.

Nutrient Availability and Solubility. The availability of manure nutrients to plants is highly variable and may be dependent upon the diet fed, environmental conditions, and soil mineralogy. In general, approximately 20 to 50% (less in semiarid, nonirrigated regions) of manure N is mineralized to plant available forms during the first year. Because most manure P is in the inorganic form [14], 60 to 90% of manure P becomes available each year [15, 16]. Manure K is usually in a highly plant available form when excreted. Van Kessel and Reeves [17] reported that the availability of dairy manure organic N was highly variable and that the phytoavailability of N could not be predicted from simple compositional differences in dairy manures. Nitrogen mineralization rates of composted cattle manure have ranged from 5 to 34% per year with an average of 20% during the first 2 yr, 10% the third year, and 5% per year for the next 9 yr [18]. Using N and P mineralization rates, they were able to develop a compost use rate for corn that would reach sustainable N and P use after approximately 12 yr of applications.

Information is limited on the availability of other minerals in various manures. Based on chemical analyses, Eghball et al. [19] estimated that plant availability of Ca and Mg in beef and swine manures was greater than 55%, whereas the plant availability of Zn, Fe, Mn, Cu, and B in manure was less than 40%. Plant available S was 23% in swine manure and 50% in beef cattle manure. Kuo [20] noted that nutrient transformations and plant uptake of Cu and Zn were more limited in poorly drained soils than well drained soils.

Phytotoxicity. Manure and inorganic fertilizers can contain high concentrations of trace minerals that are potentially toxic to plants [21]. Van der Watt et al. [22] noted that Cu, Zn, and Mn could potentially accumulate to phytotoxic levels in soils amended with poultry litter for long times. Data on speciation of As indicated that the relatively nontoxic supplemental form of As (roxarsone; ROX) used in some poultry feeds is converted to the more toxic As(V) and to unknown forms [23, 24]. However, commercial P fertilizers can also contain As and other heavy metals [21].

Effects on Other Soil Characteristics. Several studies indicate that additions of swine and cattle manure to acid soils can increase soil pH [25, 26]. This increase in pH could increase ammonia volatilization, alter N mineralization, and modify nutrient availability and solubility [25]. Some studies report that organic sources of P can modify the P sorption characteristics of soils and thus affect P movement [27]. Therefore, research on application of manures to soils needs to consider Ca, organic C, and other components of manure.

Soil Nutrient Analyses. Kamprath et al. [28] noted that most soil tests were developed to determine proper application rates of synthetic fertilizers for fertilization needs; however, today we are attempting to use many of them to evaluate potential environmental hazards. Schwartz [29] determined that this may not be appropriate, especially when nutrients are provided by manure rather than commercial fertilizer. There are considerable differences in the water solubility of P in manures, ranging from 25 to 30% in dairy manure, poultry manure, and swine slurry [30] to 6 to 13% in beef cattle manure and composted cattle manure [29, 31, 32]. Therefore, it is not surprising that soil test P using agronomic extractants is greater in soils fertilized with a soluble potassium phosphate than in soils fertilized with feedlot manure [29].

Effects of Dietary Factors. Sorenson and Fernandez [33] noted that the fiber ($r = (0.73)$ and CP ($r = 0.53$) content of swine diets affected the subsequent mineral fertilizer equivalent value of slurry N. Similarly, Sorenson et al. [34] noted that the dietary CP ($r = 0.71$) and crude fiber ($r = -0.73$ to -0.82) content of dairy cattle diets were correlated to the subsequent mineral fertilizer equivalent value of slurry N. The plant availability of slurry N was correlated with the ammonium content ($r^2 = 0.53$) and negatively correlated to the slurry C:N ratio ($r^2 = 0.67$) and DM:N ratio ($r^2 = 0.58$).

Ebeling et al. [35] noted that excessive addition of inorganic P to dairy diets (0.31 vs. 0.49%) produced manures with higher P concentrations (0.48 vs. 1.28% P). When applied at equal N application rates, total P runoff was 6 times greater, and dissolved reactive P runoff was 10 times greater for the high-P manure than the low-P manure. When applied at equivalent P levels, total P runoff was 2 times greater, and dissolved reactive P runoff was 6 times greater for the high-P than low-P manure.

Effects of Composting. Composting CAFO manure, either alone or with other agricultural or industrial by-products, has been proposed as 1 method to improve the use of manure. Composting animal manures has a number of agronomic benefits, including a decrease in application cost, decrease in mass and water content, pathogen suppression, destruction of weed seeds and feed additives, smaller and more uniform particle size, and decreased odor emissions. However, composting significantly alters the nutrient composition of manures. In general, during composting there is a 30 to 50% decrease in mass due to losses of C (46 to 62% loss) and N (19 to 42% loss) [18, 36, 37]. This decreases the N:P ratio and increases the concentration of other nutrients. The effects of composting on nutrient volatilization, nutrient leaching, and nutrient concentration can be affected by many factors, including moisture content, C:N ratio, frequency of turning, days of composting, and temperature [36, 38].

Field studies comparing fresh vs. composted dairy [39, 40] and feedlot manure [15] reported no additional effect on corn yields. Cooperband et al. [41] reported 25% lower corn yields with composted poultry litter than noncomposted litter when applied on an equal N basis. In contrast, Loecke et al. [37, 42] noted that corn grain yields were 10 to 15% greater when composted swine manure (from deeply bedded hoop structures) was used in contrast to freshly scraped manure, in part, due to a greater N fertilizer equivalency (compared with urea) for composted rather than raw swine manure. Because of these and other contradictory reports, it is not possible to clearly determine the impacts of composting on crop performance, soil quality, environmental concerns, and nutrient assimilation and accumulation.

Nutrients in Lagoons and Retention Ponds. Depending upon the type of housing and manure handling system, appreciable quantities of manure nutrients can end up in lagoons or retention ponds. Nutrient concentrations in retention ponds will vary depending upon rainfall, evaporation, changes in pond volume, and N volatilization. In general, the high concentrations of salt, P, or other nutrients in many lagoons and retention ponds limit their use as fertilizer [43, 44]. However, lagoons and retention ponds are a potential site of nutrient accumulation on many farms.

NUTRIENT LOSSES, ACCUMULATION, AND ASSIMILATION BY CROPS AND FORAGES

Nutrient Losses from Fields

Runoff and Leaching. If manures or inorganic fertilizers are applied beyond the assimilation capacity of crops or holding capacity of soil or if nutrients are improperly applied, losses by surface runoff and leaching can contribute to eutrophication of surface waters or contamination of groundwater. Nutrients potentially pose environmental problems not only where manure production or fertilizer application rates or both are high but also where environmental factors, such as rainfall, leaching potential of the soil, runoff potential of the soil, and soil erosion rates are conducive to the loss of nutrients from fields [4].

Excess nutrients applied to soils can run off pastures or fields in the soluble form in water or in the insoluble form attached to soil particles. Unlike pasture systems in which most of the P in runoff is in the water soluble form, particulate P is the dominant fraction of total P in runoff from row crop production [45, 46]. For row crops, runoff water quality depends upon soil erosion, runoff amount, manure application history, long-term tillage practices, crop residue, and P source [45, 46]. In some cases, manure application may actually help decrease runoff losses. In a summary of runoff data accumulated from 7 research stations since 1945, Gilley and Risse [47] noted that long-term applications of manure to soils increased soil organic matter and improved soil physical properties (infiltration, aggregation, bulk density) resulting in a 2 to 62% decrease in rainfall runoff and a 15 to 65% decrease in soil losses compared with nonmanured fields. Results were affected by manure application rate, manure characteristics, manure incorporation, and time between application and the first rainfall event. Under some circumstances, additional conservation practices, such as buffer strips may be effective in trapping sediments, reducing runoff water velocity, and promoting infiltration.

Volatilization Losses. Considerable quantities of N in manures can be lost to the atmosphere, primarily as ammonia. The quantity of N lost to the atmosphere during manure application is greatly affected by the method of manure application and type of manure applied and can range from less than 5% to 60% of N applied [48]. Losses from fields, pen surfaces, retention ponds, and lagoons depend upon temperature, pH, N content, and wind speed [49].

Nutrient Assimilation and Accumulation—Pastures and Forages

Application of AFO manures to pastures is normally not a sustainable method to remove nutrients because less than 20% of the nutrients applied leave the field in animal tissues or products. Only when forage is cut for hay or silage do appreciable quantities of applied nutrients leave the field. In addition, cattle do not distribute nutrients uniformly across pastures [50, 51]. Thus, fertilizer applications to livestock pastures need to be restricted in areas with high nutrient accumulations. Use of unfertilized buffer strips around riparian areas can decrease sediment runoff from pastures by 63 to 99% [52].

Poultry Litter. Many studies have been conducted to determine appropriate applications of poultry litter for optimum yield of improved pastures. Robinson [53] noted that N, P, and K application rates required for 90% of maximum Bermuda grass yield were 440, 48, and 330 kg/ha (ratio of 9:1:6); and for 90% maximum annual yields of ryegrass were 340, 34, and 280 kg/ha (10:1:8 ratio), respectively. The average N-P-K ratio of broiler litter is 2.2:1:1.3 [54]. Thus, if poultry litter is applied to meet plant N or K requirements, excess P and other nutrients will be applied.

In an uncontrolled survey of Alabama farms, Kingery et al. [55] noted that long-term application of poultry litter (15 to 28 yr at 6.7 to 22.4 Mg/ha) to tall fescue pastures increased nutrient content of fescue grass but resulted in accumulations of K, P, Ca, Mg, Cu, and Zn in the soil. Brink et al. [56] compared P, Cu, and Zn uptake of ryegrass, 3 annual small grains, 9 clovers, and 3 legumes on fields fertilized with poultry litter in Mississippi. Annual uptake of P ranged from 2 to 28 kg/ha, uptake of Cu ranged from 7 to 68 g/ha, and annual uptake of Zn ranged from 55 to 331 g/ha. However, the relative uptake was not consistent from year to year.

Scott et al. [57] found that as poultry litter application rate increased from 9.0 to 89.6 Mg/ha, the proportion of N taken up by fescue decreased from 37 to 5% of applied N. Similarly, Brink et al. [58] noted that net N uptake, as a proportion of that applied, ranged from 100 to 124% at the 9 Mg/ha rate and 64 to 76% at the 18 Mg/ha rate. Phosphorus uptake efficiency of Bermuda grass was 31 to 46% when poultry litter was applied at the rate of 9 Mg/ha and 17 to 22% when applied at 18 Mg/ha. To avoid P accumulation in the soil, litter applications would have to be limited to less than 4.5 Mg/ha. Copper uptake was less than 2% of that applied, and uptake of Zn was 7 to 15% of that applied.

Swine Effluent. Burns et al. [59] studied the effects of swine effluent application on nutrient uptake by Bermuda grass (Table 2). As N applications increased in 100-kg/ha increments from 300 to 600 kg/ha, the quantity of N remaining in the soil increased by 78, 123, 173, and 228 kg/ha, respectively. Similar relationships occurred for other nutrients studied; that is, increasing fertilization rates increased N, P, K, Ca, Mg, S, Cu, and Zn concentrations of Bermuda grass but did not affect concentration of Fe or Na. These changes were related to the increase in these nutrients in the soil profile [60].

Brink et al. [61] noted that cultivar significantly affected nutrient (N, P, K, Cu, and Zn) uptake of Bermuda grass fertilized with swine effluent; however, the relative rank of cultivars was different at 2 locations. The differences in nutrient uptake were primarily due to differences in DM yield, rather than concentration in herbage. At the lower application rate (6.5 vs. 10 ha-cm), Cu and Zn uptakes were equal to or greater than application rates; whereas at the higher application rate, Cu and Zn nutrient uptakes were only 15 and 50% of the application rates. Timing of application can also affect nutrient recovery [62].

Dairy Manure. Soder and Stout [63] noted that increasing dairy slurry application rates to orchardgrass consistently increased DM yield, soil N, and soil Mehlich-3 P, K, Ca, and Mg concentrations, although there were interactions with soil type. The actual quantities of N, P, K, Ca, and Mg removed increased with increased application rates; however, the proportion of applied nutrients removed decreased with increasing fertilization rate (Table 3). Muir [64] noted that N and P uptake by kenaf fertilized with dairy manure was relatively low, ranging from 6.8 to 10.4% of applied P. Kuo [20] noted no accumulations of Cu or Zn in Washington pasture soils that had been fertilized with dairy manure slurry for 20 yr (approximately 10 metric tons of DM/ha).

Row Crops. Houtin and Paul [65] compared the effects of 11 fertilization schemes on yield and P uptake of corn cut for silage. Hog or dairy manure composted with poultry litter was

TABLE. 2. Effects of long-term swine lagoon effluent applications on coastal Bermuda grass (Burns et al. [59])

Item	Low application	Medium application	High application
N application, kg/ha	356	670	1,340
DM yield, megagrams/ha	11.1	15.2	17.2
Annual uptake, kg/ha (% of applied)			
N	303 (85)	521 (78)	573 (43)
P	44 (30)	69 (25)	82 (15)
K	291 (68)	467 (59)	526 (33)
Ca	45 (56)	73 (48)	87 (29)
Mg	29 (52)	51 (47)	62 (29)
Cl	120 (42)	166 (30)	142 (13)
S	28	51	57
Cu	0.11 (15)	0.17 (12)	0.20 (7)
Zn	0.35 (37)	0.55 (31)	0.84 (25)
Fe	1.10	1.80	1.9
Na	4 (2)	7 (2)	7 (1)

applied to fields based on the N or P requirements of the crop. Phosphorus uptake was primarily determined by silage yield and not by P concentration in the forage.

Matsi et al. [66] fertilized winter wheat with 40 Mg/ha of liquid dairy manure (120 kg of N and 26 kg of P/ha annually) or inorganic fertilizers for 4 yr. Biomass production, grain yields, plant uptake of N, P, and K, and soil characteristics were similar for dairy slurry and inorganic fertilizer treatments. Sommerfeldt and Chang [67] and Chang et al. [68] applied beef cattle feedlot manure to barley at 0, 1 time (30 and 60 Mg/ha for dry land and irrigated, respectively), 2 times, and 3 times the recommended N rates. Even at the lowest rates, there were significant increases in soil P, Cl, S, Na, and Zn concentrations.

Ferguson et al. [69] compared long-term applications of feedlot manure or composted feedlot manure based on the N (approximately 700 kg of N and 300 kg of P/ha) or P (approximately 250 kg of N and 70 kg of P/ha) needs of corn. Corn silage yields, as well as N and P uptake by silage, were affected by level of application but were similar for manure and compost (Table 4). Applying manure on an N requirement basis resulted in accumulation of nitrates and P in the top 0.3 m of soil. Phosphorus accumulation was greater with compost than with manure because of greater P applications.

Areas Adjacent to a CAFO. Areas adjacent to a CAFO can receive appreciable quantities of nutrients via dry or wet deposition. These might be advantageous to crops or forages that readily use nutrients but may have detrimental effects

TABLE 3. Effect of fertilization with dairy slurry on orchard grass pasture mineral concentrations and nutrient accumulation in Pennsylvania (Soder and Stout [63])

	Dairy slurry N application rate, kg/ha			
Item	0	168	336	672
DM yield, megagrams/ha	3.39	4.87	6.35	8.51
Soil Mehlich-3 P, kg/ha	406	477	550	634
Soil Mehlich-3 K, kg/ha	312	529	738	958
Soil Mehlich-3 Ca, kg/ha	2,703	2,964	3,293	3,692
Soil Mehlich-3 Mg, kg/ha	235	339	420	559
Nutrient removal, kg/ha (% of applied)				
N	81	121 (72)	169 (50)	243 (36)
P	15.2	22.9 (67)	29.8 (44)	38.3 (28)
K	85	139 (112)	204 (82)	294 (59)
Ca	20	27.3 (37)	31.8 (22)	41.7 (14)
Mg	8.5	11.7 (56)	15.2 (36)	19.6 (23)

TABLE 4. Corn silage response to manure applications for a 10-yr period (Ferguson et al. [69])

Item[1]	Type of fertilizer and application basis				
	Manure N	Compost N	Manure P	Compost P	N Check
DM applied, megagrams/ha	74[b]	92[a]	20[c]	23[c]	0[d]
N applied, kg/ha	696[a]	711[a]	233[b]	261[b]	118[c]
P applied, kg/ha	259[b]	311[a]	60[c]	89[c]	0[d]
Silage DM yield, megagrams/ha	17.3[a]	17.1[a]	16.5[b]	16.6[b]	16.0[c]
Silage N, kg/ha	214[a]	214[a]	193[bc]	196[b]	190[c]
Silage P, kg/ha	42[a]	42[a]	40[b]	40[b]	33[c]

[a–d]Means in same row with unlike superscript letters differ ($P < 0.05$).

to plants that are sensitive to nutrient inputs, such as native range or forests [70]. The effects of ammonia on forests and greenhouse crops are dependent upon both the ammonia concentration and length of exposure [71].

Todd et al. [72] noted that after 30 yr of operation, dust or ammonia emissions or both from a 25,000-head feedyard had detrimental effects on native short grass prairie immediately downwind, although the effects were minimal at a distance of 500 m downwind. They calculated that daily deposition of particulates within 100 m of the feedyard ranged from 0.38 g/m^2 in the winter to 3.3 g/m^2 in the summer. Estimated N deposition decreased from a range of 19 to 31 kg/ha annually 100 m from the feedyard down to <3 kg/ha annually at 550 m from the yard. Soil Mehlich-3 P concentrations decreased from approximately 75 mg/kg at 100 m from the yard to background (approximately 15 mg/kg) at 600 m downwind.

Mining Soil Nutrients and Remediation of Soils

Many soils in the US contain excessive levels of nutrients, such as P, Cu, Zn, Se, and As due to long-term applications of commercial fertilizers, animal manure, or poultry litter. Nutrient accumulation in soils can lead to increased runoff, toxicity to plants, and can negatively impact the nitrogen fixation ability of legumes [73]. Thus, under some circumstances, it may be necessary to develop a management plan to remove excess nutrients from the soil while still producing a potentially profitable crop.

Plant Variations in Nutrient Uptake. Some plant species assimilate and accumulate soil nutrients more effectively than others. In some cases, the increased accumulation of nutrients is determined by total DM biomass yield; whereas in other cases the changes are due to increased nutrient concentration (i.e., luxury uptake) in the plant. For example, in Mississippi, Rowe and Fairbrother [74] noted that the legumes berseem clover and red clover yielded up to 64% more N, 24% more P, 40% more Zn, and 73% more Cu than ryegrass. In Texas, McCollum and Bean [75] reported that annual P removal by sorghum and corn silage hybrids ranged from 34 to 64 kg/ha. Phosphorus removal per unit of irrigation water used was 50 to 150% greater for forage sorghums than for corn silage. Eghball et al. [76] and Schmidt et al. [77] noted varietal differences in nutrient uptake by soybeans and corn fertilized with manures. Over a 2-yr period, there was as much as a 54% difference among corn hybrids in P removal by grain.

With Bermuda grass pastures, Evers [16] noted that overseeding annual ryegrass removed twice as much P as Bermuda grass. Overseeding with annual ryegrass increased annual P removal by approximately 25 to 40 kg/ha. Pederson et al. [78] noted that N and P uptakes were similar for ryegrass, cereals, and legume pastures fertilized with poultry litter. Potassium uptake was approximately 60% less in legumes than in grasses; whereas Cu uptake was approximately 30% greater in legumes.

Adjusting Application Rates. Whalen et al. [79] reported that manure applications to fields should be adjusted based on the increase in potentially mineralizable N and P from past manure applications. Eghball et al. [76] applied feedlot manure and composted manure to corn fields for 4 yr based on the N needs or the P needs of the crop to obtain soil Bray-1 P concentrations, ranging from 50 to 270 mg/kg of soil. Corn

TABLE. 5. Effects of ammonium nitrate in combination with poultry litter [9 megagrams (Mg)/ha] application on N, P, and K recovered in Bermuda grass overseeded with annual ryegrass (Evers [16])[1]

Commercial N applied (kg/ha)	N recovered (% of applied)	P recovered (% of applied)	K recovered (% of applied)
0	45	21	64
56	48	22	78
112	51	25	88
168	52	27	95
224	50	27	98

[1]Nutrients applied in poultry litter = 341 kg of N/ha, 203 kg of P/ha, and 332 kg of K/ha.

was then grown an additional 4 yr with only N fertilization. The calculated time required to lower soil P concentrations to the original values ranged from 0 to over 10 yr. Corn grain removed a maximum of 36 kg of P/ha with an average 4-yr total of 107 kg/ha. The quantity of P removed annually by corn hybrids ranged from 26 to 41 kg/ha, and P removal by soybeans ranged from 17 to 22 kg/ha. Nitrogen fertilization increased P removal by 2-fold due to an increase in yield.

Combining Organic with Inorganic Fertilizers. On soils with high P concentrations, fertilizing with a combination of organic fertilizers and an inorganic N source could potentially increase P uptake, remediate high soil P, prevent accumulation of P or other nutrients, and may even be more profitable [80]. Evers [16] studied the effects of combining ammonium nitrate fertilization with broiler litter application to increase P and K removal using Bermuda grass-ryegrass pastures (Table 5). Applying commercial N fertilizer in combination with litter increased DM yields and thus increased P uptake by 23% and K uptake by 43% compared with using no N fertilizer. Approximately 45 to 52% of applied N was recovered in harvested forage. The percentage of K and P applied in the poultry litter that was recovered in plant biomass increased as N fertilization rate increased. Although results varied somewhat from 1 location to another and from 1 year to another, on average Coblentz et al. [81] noted that P uptake of Bermuda grass increased linearly as N fertilization increased from 0 to 224 kg/ha. Soil P concentrations could be decreased 10 to 20 mg/kg annually using this strategy.

Trace Minerals. Significant quantities of trace minerals and heavy metals can be applied to soils with manure and inorganic fertilizers [21, 82]. In an assessment of the distribution of heavy metals in soil profiles of agricultural areas with a 25-yr history of poultry litter applications, Han et al. [83] noted that Cu, Zn, and Mn accumulated close to the soil surface at concentrations as much as 10 to 20 times of those for unamended soils. Copper was present mostly in the organic matter fraction (47%), whereas Zn was mostly in the easily reducible oxide fraction (47%). Thus, Cu and Zn were potentially bioavailable and mobile.

Most of the research available on remediation of soils high in trace metals involves sewage sludges and biosolids. In general, biosolids application has had variable effects on crop yield and plant concentration of N, P, K, Ca, Cu, Mo, Mn, Ni, or Zn. Although biosolids sometimes increased soil concentrations of some micronutrients, their phytoavailability remained low [84, 85, 86, 87, 88]. Somewhat in contrast, Wilkinson et al. [89] reported that potentially toxic accumulations of Cd occurred in the kidneys of sheep grazing on sewage sludge-fertilized pastures due to increased herbage concentrations of Cd, Pb, Cu, and Zn.

CONCLUSIONS AND APPLICATIONS

1. In some areas of the US, continued inputs of fertilizer and manure nutrients in excess of crop requirements have led to a buildup of nutrient concentrations, which is an environmental concern.
2. Losses of nutrients, such as P can be reduced by refining the rations fed, increasing nutrient retention by livestock, moving manures from areas of surplus to deficiency, finding alternative

uses for manure, using cropping and haying systems that remove excess nutrients, incorporating manure immediately after application, and using conservation practices, such as limited tillage, buffer strips, and cover crops to limit runoff and leaching.

3. Progress has been made. In the past 3 decades, the total quantities of manure N and P excreted by US dairy cows [3] and fed beef cattle [90] have decreased by as much as a third, thanks to improved feed conversions. In Wisconsin, annual P excess (i.e., soil storage) decreased from 54 million kg in 1975 to 14 million kg in 1995 [91].
4. Whole-farm nutrient balances can be a useful tool for producers to estimate the quantity of nutrients entering and leaving a farm and to identify major nutrient flow paths. However, spatial factors, such as uneven nutrient application can cause an environmental risk not noted by a total nutrient balance [92].
5. Although a balance between manure nutrient application and crop uptake is essential to develop sustainable manure management practices, even under the best systems, some nutrient loss is inevitable [93, 94].
6. A major factor limiting use of manure nutrients is often farmers' preference for inorganic fertilizers.
7. Thus, to make it more attractive as a fertilizer, livestock and poultry producers need to treat manures as a coproduct, rather than as a waste to be disposed of at the cheapest price.

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